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Harvesting Energy from Rain Drop through Application of PZT Material: A Review

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Abstract: ***In recent years there has been an increased interest in scavenging energy using alternative sources. Renewable energy such as solar, wind, biomass, hydro and tidal wave are studied and implemented all around the globe. One of the potential sources of energy is rain. The common way to generate energy from this source is by utilizing dam system. Although it is very effective and the electrical energy generated by it is promising but it is not applicable or worth to be implemented everywhere especially in remote areas. studies have shown that the vibration produced by raindrops at the moment of impact is quite promising. This vibration can be harvested and one of the methods introduced in this paper is PEH (piezoelectric energy harvesting) technique, which can be used to capture vibration, motion or acoustic noise, to be converted in to electrical output. This review paper aims to provide a fundamental study on the behavior of raindrop, the potential energy it carries, the meteorological data and the types of impact. This investigation leads to a better understanding of these natural phenomena that helps the researchers to design a better configuration of PEH system and consequently obtaining greater output energy has been addressed.***

Keywords: Renewable energy, Harvesting energy, Raindrop, Piezoelectric

1. Introduction

It is true that the global energy consuming systems are extremely dependent on fossil fuels but over the past few years, the demand of renewable energy sources has significantly increased. Renewable energy sources are extensively used due to some of the disadvantages of fossil fuels such as, environmental damage, territorial imbalances and fossil fuel depletion which caused this global shift towards clean energy [1–4]. Among different sources of renewable energy fuel cells are the most promising due to the heat power generation advantage and many researchers studied it's variety usage from handheld devices to residential use [5–7].

The combination of growing demand for energy in developing country as well as growing interest in renewable energy and their reliable works has forced researches to find new ways of producing energy without the use of conventional thermal power [8,9].

One of the potential sources of renewable energy that draws the researcher's attention is rain. Rain is a natural phenomenon that exists and occurs in day-to-day life. The most common method to harvest energy from rainwater is using dam that reserves the water at a greater height and leads it through hydro turbines, which converts the kinetic energy into electrical power. Even though the output power is promising but it is limited since it requires a proper geographical location, preservation concern and its impact on plants and animal life [10].

Another way of harvesting energy from this phenomenon is by considering the kinetic energy possessed by the raindrops, which is discussed in this paper. The kinetic energy is stored in raindrops as they are falling from high altitudes [11]. Although this kinetic energy stored in the raindrops cannot be harvested entirely but it is possible to harvest a portion of this mechanical energy through exploiting the vibration produced upon the impact [9].

Since this method of harvesting relies strongly on frequency and volume of rainfall. Those regions, which have heavy rainy seasons, are suitable for this method. Malaysia is one of the countries which is located in equatorial and because of that it receives massive rainfall throughout the year [12]. This makes it suitable to apply this technology especially in remote areas where the accessibility to electricity is difficult. It is seen that the demand has increased rapidly in self-powered electronic devices such as wireless sensors, industrial automation, and electronic devices.

In most cases, a conventional electrochemical battery and/or capacitor are used to power such applications. Although both components are used to store the electric energy, there are few characteristics that distinguish from one another and make them suitable for specific energy harvesting applications. Comparing to batteries, capacitors have been used by researches in many applications as the main energy storage medium [13,14].

It is clear that capacitors can be charged and discharged quickly unlike rechargeable batteries, and it is due to their high power density, which enable them to provide accumulation. However, it must be taken into account that their voltages decreases quickly as they discharge and that is why they have lower energy densities [15,16].

On the other hand, in applications where there is a need of self-power generator. This kind of battery is no longer suitable because of few deficiencies such as having a short lifetime, limited power storage, maintenance issues, and large weight and size compared with the device they power. Most importantly, when the battery is completely flat it must be replaced. So, to overcome these problems it is better to utilize energy from environmental sources which includes thermal energy, solar energy, wind energy, hydroelectricity and vibration energy [17–20].

Currently there are three methods being used to convert the mechanical energy from vibration into electrical energy namely as electromagnetic [21,22]induction, electrostatic [23,24]induction and piezoelectric effect [25,26].The studies on piezoelectric materials have been most widely investigated since they provide higher density and can be readily integrated into a system [16,27,28].

The technique being proposed in this paper to convert the vibration energy into electricity is from one of the categories of energy harvesting (EH). EH techniques at the micro-level can mainly be categorized into three forms: piezoelectric, thermo- electric and photovoltaic [29].

The fact that this energy produced at the moment of raindrop impact with a surface low-energy, millimeter-scale drops has led to consider a system of piezoelectric recovery sensitive to weak energy sources.

In conversion of mechanical energy to electrical energy piezoelectric materials are already extensively used, and have recently been applied to various environmental energy scavenging scenarios: for example, in a windmill, the blades are equipped with piezoelectric material to maximize capturing wind energy [9].

Comparing to other methods used, the piezoelectric approach is the most suitable one; there are variety of reasons for that, such as, its availability in many forms, including piezoceramic, single crystal, screen-printable thick film using piezoceramic powder, thin film and polymeric material and most importantly it allows us to convert vibration energy directly into electrical energy without using any external power supply [30].

As it is mentioned the piezoelectric materials come in various types. The most common types of piezoelectric material being used are polyvinylidene fluoride (PVDF) [31,32] and lead zirconate titanate (PZT) [33,34].

The most well-known piezoelectric material, which is widely used, is PZT (Lead Zirconate Titanate) but due to its nature that is extremely brittleness it causes some limitations. In the case of harvesting raindrop energy, the piezoelectric membrane is subjected to a high frequency cyclic loading that makes it susceptible to break. To overcome these issues a piezoelectric material, which has a lighter weight, shows more flexibility with low acoustic and exhibit mechanical impedance is introduced. PVDF (Polyvinylidene fluoride) has all the properties mentioned and is adequate [35], but in this special case which the material engages in direct contact with water and due to the high sensitivity of the system, PVDF materials are recommended.

In a research, which investigated the performance of these two materials [11], the efficiency of two similar structures for both PVDF and PZT was compared and it was concluded that PVDF materials are more suitable.
In order to have a better understanding of the parameters that affect the energy output generated from REH devices it is essential to study and investigate the theories behind the phenomena called rain. One of the parameters affecting the energy output is the velocity of raindrop at the moment of impact.

There are three factors which can affect the energy output of REH devices, mass of the droplet, volumetric size, the mechanism of impact and velocity at which it strikes the device's surface. The radius of course depends on geographical location and it can vary between 1 mm and 5 mm [29,36].

2. Literature Review

This section provides a review about the previous works done by researches. In order to have a better understanding of the topic, this information is categorized according to their relevance on matter. These subsections are arranged in the following order; the behavior of droplets before impact, the types of impact, meteorological data, calculating the kinetic energy carried by droplets and finally different configuration of piezoelectric.

2.1 Behavior of a Raindrop

As a raindrop in free fall reaching the ground undergoes two different forces that are exerted upon it. These forces which are exerting vertically on it, are in opposite of each other. The force acting upwards is called drag force, and the force, which is acting towards the ground, is known as gravitational force. As the raindrop reaching the ground at a certain point the values of these two forces balance each other. At that point where the forces of gravity and resistive forces are opposed equally, it said that raindrop has reached its terminal velocity. Fig 1 shows the shape of the raindrop resulting from all the forces acting upon it [29].

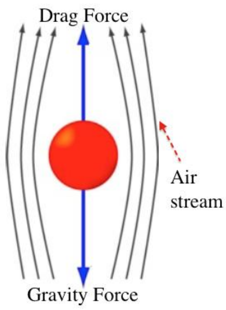

Figure 1: The gravity force and drag force acting upon raindrop [29]

As it is observed from the Fig.1 the shape of the raindrop looks like an oblate spheroid, which is different from popular belief. The reason which raindrop behaves this way and changes it's shape is in fact caused by air resistance, which changes according to the diameter of raindrop. The raindrop has almost spherical shape for drop sizes of 1mm and less but it shapes gradually deforms and looks like a hamburger bun as illustrated in Figure 2 [37].

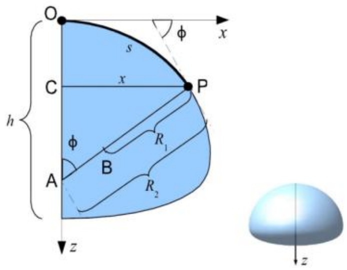

Figure 2: Diagram of curve for the drop surface in the x-z plane with radius of curvature R1 given by BP and R2 by AP (both lying on the perpendicular to the curve at P)[38,39]

The following equation has been derived from aerodynamic pressure on raindrop [38]:

$$\sigma d\phi = -\sigma \sin(\phi/x) + 2\sigma/R_t + \Delta\rho g z + (p_i)_t + (p_a)_t \quad (1)$$

This changing shape will continue until it breaks up into smaller pieces. According to Newton's second law of motion which states that the net forces on a particle are equal to the time rate of change of its linear momentum, the below equation can be written [29].

$$F_n = \frac{d}{dx}(mv) \quad (2)$$

Therefore,

$$F_n = m\dot{v} \quad (3)$$

The drag force acting on raindrop can be obtained from the following equation,

$$F_{air} = \frac{1}{2}\rho_a A C v^2 \quad (4)$$

Where ρ_a, A, C, v representing the density of air, Cross-sectional area, Coefficient of drag and velocity respectively. The gravity force acting vertically downward obtained by,

$$F_{gravity} = \frac{4}{3}\Pi r^3 \rho_w g \quad (5)$$

Where r, ρ_w, g representing the radius of droplet, density of water and the acceleration of droplet due to gravity respectively. By equating the right sides of equations (4) and (5) the terminal velocity can be verified as:

$$v = \sqrt{\frac{\Pi d^3 \rho_w g}{6\rho_a AC}} \quad (6)$$

It can be derived from the formula above that the terminal velocity depends on the raindrop diameter (d) and the drag coefficient (C). The formula is valid if the shape of raindrop assumed to be spherical which in reality is not true. For the droplets with radius of more than 8mm it tends to break up into smaller droplets. Figure 3 illustrates how the shape of the droplet varies according to its size. This clearly shows that the deformation of falling drops is determined by competition between surface tension and fluid stresses [40].

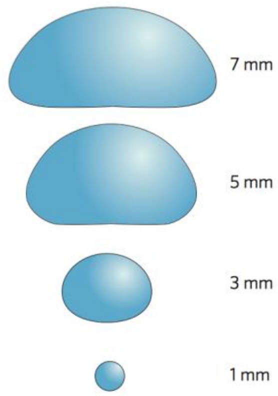

Figure 3: Deformation of falling drops according to their sizes [40]

2.2 Meteorological Results

In terms of intensity, the classification of rain can be categorized into the following; heavy thunderstorms (HT), moderate stratiform rain (MSR) and light stratiform rain (LSR) [41]. Table 1 shows the values of raindrop sizes as well as the experimental terminal velocities

Table1: Comparison of drop size and terminal velocity of rain types [41]

Rain type	Drop size (mm)	Terminal velocity (Experimental) (M/s)
Light stratiform rain		
Small	0.5	2.06
Large	2.0	6.49
Moderate stratiform rain		
Small	1.0	4.03
Large	2.6	7.57
Heavy thundershower		
Small	1.2	4.64
Large	4.0	8.83
Largest	5.0	9.09

Another important factor that must be taken into account is the number of raindrops per unit area per unit time. Table 2 reveals this value for each category of rain type.

Table 2: Number of raindrops per unit time on unit area [41]

Rain type	Number of rain drops (per 1s on $1m^2$)
Light stratifrom rain	280
Moderate stratifrom rain	495
Heavy thundershower	818

The country of Malaysia is located in equatorial and it is blessed with abundant rainforests. It is separated into two geographical portions namely as West Malaysia, the southern third of the Malay Peninsula in south east Asia and East Malaysia, which occupies the northern quarter of the island of Borneo [42].

Malaysia is in the end phase of Southwest Monsoon before inter-monsoon period. Normally, during this period some places in Malaysia will experience heavy rainfall and thunderstorms in the evening. Most places in Peninsular Malaysia recorded normal amount of rainfall during this month. However, a few places in northern part of the peninsula recorded much above normal rainfall amount ranging from 350 mm to 500 mm. The highest monthly rainfall with a total of 496.2mm and 455mm was recorded in September and it belongs to Butterworth and Prai respectively. Over Sabah and Sarawak, most places received normal amount of rainfall ranging from 100 to 450mm [43]. The recorded monthly rainfall of the entire year is shown in Figure 4.

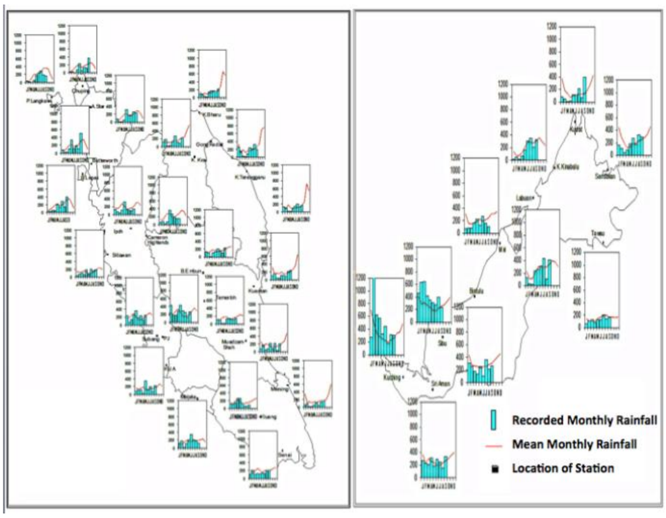

Figure 4: Recorded Monthly Rainfall of the Year 2016 in Malaysia Monthly Rainfall Review[43]

2.3 Types of Impact

Immediately upon the collision of raindrop with a solid surface one of the following might happen: splashing, spreading and bouncing which is shown in Fig [5]. Drops colliding with surface might stick to the surface or even bounce off it; they also could break up or splash. It is in fact because of these different actions that decentralization of the droplet occurs. The topic of interest here is those conditions which lead to splashing and spreading because of the affect they could have on the outcome of EH system. Many studies carried out to predict this behavior [6], Stow and Hadfield developed a splash parameter as the splash is emerging and it is determined by surface roughness. This value is contingent upon the surface roughness. Mundo et al [7] by conducting experiment found the boundary between the splashing mode and deposition mode for rigid impact surface. Equation (7) represents this relationship.

$$K = Oh \times Re^{1.25} > 57.7 \quad (7)$$

Where Oh and Re are Ohnesorge and Reynolds number respectively, 57.7 is called the empirical value and splashing occurs and by passing this value splashing will occur. But this formula is not actually accurate since it does not take into account the surface roughness. An experiment conducted on a rigid impact surface by Thoroddsen and Sakakibaras [8], they have realized that under the same experimental condition in Mundo's splashing establishment splash did not occur. They have concluded that surface roughness is correlated with occurrence of splash in way that the rougher the surface the chances of splashing near the line of splash is higher.

In addition a study carried in India [44], to investigate the behavior of droplets on a rough structured surface and it was observed that as the droplets are spreading on smooth surface the produce a circular pattern, while for the similar experiment on rough surface (textured substrate) the pattern appeared to be in a shape of rhombus. In case of lower Weber number (We) the rhombus shape is regular. In contrast the shape becomes more complex for higher Weber number (We). Also, the values of spreading diameter and the liquid volume flowing on the rough surface was measured and compared to similar case for the smooth surface. The number obtained was smaller and it is mainly due to the deduction of kinetic energy as it spreads on the surface. [45]

Mundo introduced another phenomenon, which is the occurrence of the corona. It is a condition where at the moment of impact a thin layer is formed and tiny droplets appears on its upper rim. An experiment to investigate the break up and deformation of droplets were carried [46], on two types of rough and smooth surfaces with varying the Reynolds number. On smooth surface with high Reynolds number the corona was formed and stretched in its radial expansion while for the case of low Reynolds number the kinetic energy to overcome surface tension and gravity to form a corona is dissipated. On the other hand, for the case of rough surface and having a low Reynolds number it was found that the concentration of the secondary droplets is much higher in front of the impingement point, and for the range of low Reynolds number the surface roughness does not promote the splashing of the primary droplet. The possible scenarios of drop impact on a solid surface are illustrated in Figure 5.

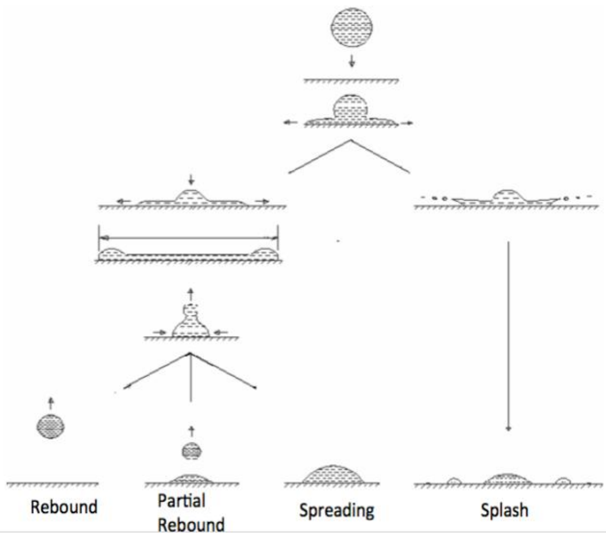

Figure 5: An illustration of possible behavior of droplets after the impact [47]

One of the important factors which must be taken into account is wettability of the surface [48–50], the complexity of these factors combined together makes it impossible to make a precise prediction about this phenomenon.

In a research conducted to understand how leaf surface wettability affects the bending energy and torque on the leaf during raindrop impact, which can cause damage and contribute to early leaf fall. A cantilever beam was designed to go under same process as the droplet falls on it. The results show that beams with a super hydrophobic (θ > 150°) surface undergo zero average torque over time since the impacting drops either bounce or roll off, while due to sticking of the impacting drops on hydrophilic surface experience a torque proportional to the drop weight and beam length [51]

There are other surface characteristics that affect the output result of EH device such as impact angle. An experimental study by Sikalo empirical correlation was found in which explains the rebounding of droplets only observed on dry smooth glass and on wetted surfaces, while on dry smooth wax and rough glass the behavior of raindrop was differently and no rebounding occurred [52].

2.4 Calculating the Kinetic Energy

The purpose of this study to study the possible methods of converting the vibrational energy generated by droplet at the moment of strike to electrical energy and of course this requires using a proper PEH device. But before that it is important to know about the amount of energy, which the droplet carries out after reaching equilibrium at a certain stage. According to equation (8) the amount of kinetic energy is related to velocity and droplet size. And the velocity of the droplet is directly proportional to its diameter meaning which, the larger the droplet, the faster it falls [8,9].

$$E_{KE} = \frac{1}{2}\rho_w \left(\frac{4}{3}\pi\left(\frac{d}{2}\right)^3\right)v^2 \qquad (8)$$

Where d is diameter of droplet, v is droplet terminal velocity and ρ_w is water density [10]. The assumption made is that the volume of the raindrop remains constant during the fall and is perfectly spherical in shape.

It is not possible to extract all this energy, due to occurrence of splashing which cause most of the energy to be lost. But there are few ways to optimize the harvester and reach the resonance frequency for a better result [53].

As a result of the vibration in the piezoelectric material a charge Q is generated which later via two electrode plates is collected. The voltage U created across the plates is given by,

$$U = \frac{Q}{C_{piezo}} \qquad (9)$$

Where C_{piezo} is the capacitance and can be calculated using,

$$C_{piezo} = \frac{\varepsilon_r \varepsilon_0 A}{t} \qquad (10)$$

Where, $\varepsilon_r, \varepsilon_0, A$ and t are representing the electrical permittivity in vacuum, the relative permittivity of the medium between plates, the electrode area and the separation of the electrode plates respectively [45]. Therefore, the generated power is framed by,

$$P = \frac{E}{t_{impact}} \qquad (11)$$

Where the stored energy E is obtained by,

$$E = \frac{C_{piezo} U^2}{2} \qquad (12)$$

And t_{impact} is the period of the impact on piezoelectric structure.

2.5 Different Configuration of Piezoelectric

Piezoelectric materials exhibit electromechanical coupling, which is useful for design of devices for sensing and actuation. Due to having this property it generates electrical polarization in a material in response to a mechanical stress. This property is called direct effect since the mechanical to electrical coupling was discovered first [54].
Piezoelectric materials also display the converse effect; mechanical deformation upon application of electrical charge or signal [55].

To harvest high amount of energy by piezoelectric harvester, it requires a proper selection of material, which in that case flexible piezoelectric materials are more attractive since they are able to withstand a large amount of strain. This specific characteristic yields to having more mechanical energy to be converted. Another way of increasing the amount of energy harvested is by utilizing an efficient coupling mode [27].

It is essential to use a proper method of coupling related to the application in order to increase the energy harvested by the system.

Practically, there are two types of coupling, 33 mode and 31 mode. Figure 6 illustrates the concept underlying these two modes. By labeling x, y and z axis as 1, 2 and 3.

33 mode is the one in which the direction of force applied is perpendicular to the direction of poling. A bending beam that is poled on its top and bottom surfaces is an example of which. On the other hand 31 mode is when the direction of poling is same as the direction in which force is applied. The common example would be bimorph in where two beams are bonded on top of each other.

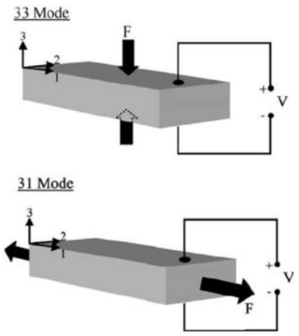

Figure 6: Illustration of -33 mode and -31 mode operation

The 33 mode provides a higher coupling coefficient than 31 mode: however, the most common type of coupling is 31 mode and its due the fact that system operating in this mode is more compliant, therefore making it possible to produce larger strains with smaller input forces [56].

In a research conducted by Brake [57], the 31 mode cantilever beam was compared with a new design of 33 mode piezoelectric stack theoretically and experimentally.

The power output generated by these two methods was investigated using the same applied forces as well as reasonable geometries for both devices. In terms of strain to energy conversion a higher rate of reading was observed for the 33 mode piezoelectric stack. Even though inducing power is difficult this mode, however in a high force application it has higher efficiency because it is more robust. In addition a cantilever beam having a shape of trapezoid was tested which despite the hard process of its manufacturing; it made a suitable choice for applications where low vibrations exist. Another important factor that must be considered in pursuance of maximizing the output power is to match natural frequency as closely as to the fundamental frequency of vibration.

3. Conclusions

The abundance of rain fall in Malaysia makes it a promising and reliable source of energy which with proper investigation and studying its nature could be scavenged and be used in many applications as well as agriculture and household in remote area.

The pressure produced by rainfall can be simulated as almost the same as using finger pressure. If the finger is pressed firmly, it could duplicate the heavy mass of water during heavy rainfall for each droplet. The generated vibration caused by droplet impact can be harvested by using EH devices. The result of previous studies shows that among all the methods discovered, piezoelectric materials are more suitable and among them PVDF is more favorable due to generating a greater amount of power compared to PZT. It is clear that the droplet might go under one of the following scenarios as it strikes the surface: splashing, spreading, rebounding and partial rebounding. It is important to know that raindrops behave differently in each of these situations, knowing the dynamic of impact while considering the surface condition and coefficient of collision will provide a better understanding on harvesting and scavenging the energy generated.

Researches encounter such dilemmas when it comes to harvesting the vibrational energy using piezoelectric material, and the answer of all these challenges lies in taking into account the real world situation rather than environmental or ideal cases which only can be done by proper mechanical designs. One of the issues would be matching the fundamental and natural frequencies, which itself could be quite challenging in micro-power scenario. Employing bi-stable mechanism could be one of the potential approaches in solving this issue. This is a good topic among the challenges to be investigated by future works to create a more general solution, which brings us one step closer to the idea of powering wireless sensors in real applications.

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